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Abstract

A general approach to evaluating the technology maturity of Generation IV (Gen IV) reactor systems has been developed for the Gen IV program. Other technology maturity evaluation systems were studied for their applicability to this system. The maturity evaluation method developed is based on the methodologies studied but with increased granularity in the basic research domain. The method was used to evaluate the results of forty-two reports associated with a particular Gen IV system, and the technology maturity measurements were summarized. Weaknesses in the evaluation are discussed, whether they arose from the method used or the report development. Six recommendations on improvements to both the evaluation method and report development methodology are provided. Follow-on work, including application of the improved evaluation methodology to the rest of the Gen IV domain, is also described.

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Executive Summary

The Generation IV Nuclear Energy Systems Initiative (Gen IV) program is researching multiple reactor types to advance nuclear reactors into the 21st century and beyond. Gen IV includes a systems analysis activity that provides assistance to the program managers regarding making the most efficient progress towards achieving Gen IV outcomes.

Part of the role of the systems analysis activity is to develop and apply a methodology for evaluating the status of research and development (R&D) for the Gen IV reactor types. The R&D for the various reactor systems is aimed at eliminating uncertainties in the viability of the operations of these reactors prior to arriving at a decision point when only the viable reactors will proceed. Ensuring that the R&D is resolving the uncertainties in a timely manner to allow for such a decision point is crucial to the success of the program. This report documents the prototype application of the approach taken to evaluate that progress and the results of applying the approach to a specific Gen IV reactor system.

In general, the progress assessment methodology follows the approach of assigning a technical readiness level (TRL) to the reactor system and updating that TRL as R&D tasks are completed. There are many examples of TRL scales and their application to systems of varying and evolving maturity. Upon examining these systems and comparing the Gen IV needs, it was determined that an emphasis would be placed on having sufficient levels at the earlier development stages so that the Gen IV R&D progress can be more easily recognized. Furthermore, it was understood up front that evaluating Gen IV systems for their TRL would be challenging due to the varying levels of TRL within each Gen IV system. Some sub-systems and components within a Gen IV reactor may be well understood due to their similarities to Gen III and Gen III+ systems, while other sub-systems and components are completely new and require tools to be developed to be able to even evaluate their effectiveness.

Documents providing results from FY-05 research for the Very High Temperature Reactor (VHTR) system were evaluated and TRLs established based on the information provided in those documents. Generally, the information showed research being conducted at a very basic stage, including development of material testing standards, material property databases, initial fluid flow and thermal modeling, as well as uncertainty analyses based on calculating reactor neutronic parameters. As stated, while the tasks focused on less mature aspects of the VHTR and, subsequently, the TRLs indicated a low level of technical readiness, it was confirmed through discussion with project management that many other aspects related to the design of the VHTR system are well understood and not documented because research is not ongoing in those areas.

As a result of this prototype application of the TRL evaluation methodology, several recommendations were developed. Related to the TRL methodology itself, it is recommended that contact with program personnel, including principal investigators and possibly the System Integration Manager, is necessary to supplement the knowledge gleaned from the technical reports. The reports themselves can be structured with little additional effort in a way that more clearly identifies the purpose of the R&D in terms of advancing the reactor concept and the outcome of the effort in the context of the purpose.

Although contact with program representatives is recommended to fill in the blanks, effort should also be invested to identify the basis and documentation associated with “mature” aspects of these reactors so that, upon initiation of upcoming decision-making or in the design process, the information can be retrieved and used to the benefit of the Gen IV program. That information, combined with current understanding of technical gaps, should be combined into a detailed R&D plan from now through at least the viability phase, to ensure the success of this phase of the Gen IV program. Such a plan would be invaluable in rating the progress against a consistent yardstick.

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Acronyms

AFCI	Advance Fuel Cycle Initiative
BOP	Balance of Plant
FY	Fiscal Year
GEN IV	Generation IV Nuclear Energy Systems Initiative
GNEP	Global Nuclear Energy Partnership
LWR	Light Water Reactor
MHR	Modular Helium Reactor
NA	Not Applicable
PIs	Principal Investigators
R&D	Research and Development
SIM	Systems Integration Manager
TBD	To be determined
TRL	Technical Readiness Level
VHTR	Very High Temperature Reactor

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Prototype Application of Gen IV Technical Maturity Assessment Methodology

1. Purpose

The FY-06 Systems Analysis goals were defined in the "Generation IV Nuclear Energy Systems Initiative Systems Analysis FY-2005 Year-End Report" [Dixon & Soto, 2005]. The report states, "Systems Analysis responsibilities include completing development of the technical maturity evaluation approach, testing it on one Gen IV system/variant, and reporting the results…" This document executes that responsibility, and documents the evaluation approach and the results of applying it to the Gen IV system, as well as an evaluation of the approach itself and recommendations on improving the methodology.

2. Background

The Generation IV Nuclear Energy Systems Initiative (Gen IV) program was initiated by the development of a technology roadmap in 2001-2002[1]. The roadmapping effort included collecting and screening numerous nuclear reactor concepts, investigating and evaluating the top twenty concepts, and down-selecting to six systems for research and development (R&D).

Two phases of R&D were envisioned during the roadmap:

- A Viability Phase when basic physics, chemistry, and materials requirements would be explored and system designs modified to remove any "show-stopper" issues

- A Performance Phase when system designs would be matured and optimized through scale experiments and focused design and analysis activities.

Formal evaluations and down-selections were planned for the end of each of the R&D phases to reduce the number of systems/variants moving into the more expensive performance phase and on to selecting the systems for large-scale deployment. The evaluation methods and tools would be refined and tools developed in parallel with the R&D efforts.

2.1 Scope

In FY-05, the Gen IV Systems Analysis group was tasked with coordinating the in-process evaluation of the technical maturity evolution of the systems to ensure that the systems are on track toward being ready for the performance evaluations mentioned above. The actual process of evaluating the performance of the reactor systems at those key decision points (i.e., end of the viability and performance phases) is addressed by the Economics Modeling, Proliferation Resistance and Physical Protection, and Risk and Safety working groups within Gen IV and is not treated here.

The Systems Analysis task is to create a viable prototype methodology and process for measuring the technical maturity of Gen IV reactor systems and for tracking the results of the various R&D tasks to ensure program management that the systems are progressing appropriately toward being able to be evaluated at the key decision points. The prototype was applied to a single reactor system to test its

[1] "A Technology Roadmap for Generation IV Nuclear Energy Systems", issued by the U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, GIF-002-00, December 2002.

efficiency in assessing the maturity of a Gen IV system. The results of the prototype application were reviewed, and modifications to the methodology were developed to enhance its deployment across the Gen IV systems.

2.2 General Approach

The approach taken to evaluate the progress of technical maturity of the Gen IV systems was to apply a model of Technical Readiness Levels (TRLs) to the results of the R&D tasks. The R&D results were identified by perusing and summarizing the reports associated with the Gen IV system in question. The report summaries were then evaluated against the TRLs to identify a TRL result as represented by the work scope accomplished in the R&D task, as documented. Those TRL results were compiled and represented.

3. Methodology Development

A methodology and associated process was required to execute the technical maturity assessment approach. This included the development of

- An applicable TRL scale
- The process of identifying, summarizing, and using R&D results
- The visualization of the results in the context of Gen IV maturity.

3.1 TRL Scale

Many structures and models exist that define TRLs for developing systems. The FY-05 Systems Analysis report provided the TRL scale used by the Advanced Fuel Cycle Initiative (AFCI) program. A generic version of that scale is provided in Table 1.

Table 1. Generic TRL system - from the AFCI 2005 draft Program Plan

TRL	Category	Description
1	Concept Development	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development.
2		Practical applications are invented. Applications are speculative, and there may be no proof or detail to support assumptions.
3		Active R&D is initiated. This includes analytical and laboratory studies to physically validate analytical predictions or separate elements of technology.
4	Proof-of-Principle	Integration of basic technological components for testing in laboratory environment. Includes integration of “ad hoc” hardware in the laboratory.
5		Integration of basic technological components with realistic supporting elements for testing in relevant environment.
6		Model or prototype system testing in relevant environment.
7	Proof-of-Performance	Demonstration of prototype system in an operational environment

TRL	Category	Description
		at the engineering scale.
8		End of system development. Technology proven to work in operational environment at the engineering to full scale.
9		Full-scale application of technology in its final form at mission conditions.

This TRL scale is applicable to any system development as it covers the range from basic science to scaled, long-term demonstrations. Upon evaluation for applicability to Gen IV systems, however, it was determined to be lacking in granularity in the early stages. It is recognized that developing a next generation nuclear reactor system requires a great deal of work, including basis scientific research and understanding. Some systems have many common elements to current reactors but also require materials that have never been used or tested. Other systems would employ completely new concepts that have never been demonstrated above the smallest scales or not even beyond computer simulation space. In either case, basic research is needed to advance some or most of the components and sub-systems in these reactors.

3.1.1 Expansion of the TRL Measurement Scale

The TRL scale of Table 1 addresses the full range of technology. To see annual progress in the Gen IV Viability stage, more levels are required at the basic research and concept development phases.

This issue of ability to detect maturity measurement in the viability phase is further demonstrated by the endpoints of that phase, as identified in [Schultz, 2003]. As shown in Table 2, Goals 1, 2, 3, and 6 are mostly focused on design elements of the applicable Gen IV system. Most engineers would prefer to rely on empirical data for use in developing the elements of a design, even at a “pre-conceptual” stage of development. One could argue that a simplified preliminary environmental impact statement (Goal 7) would also rely on the results of testing and design elements. However, goals 4, 5, 8, and 9 (with particular emphasis on goals 5 and 9) show that certain methodologies, tools, and techniques require development in order to mature the Gen IV system.

Table 2. Gen IV Initiative Viability Phase Endpoints

Viability Phase Endpoints:
1. Preconceptual design of the entire system, with nominal interface requirements between subsystems and established pathways for disposal of all waste streams.
2. Basic fuel cycle and energy conversion (if applicable) process flowsheets established through testing at appropriate scale
3. Cost analysis base4d on preconceptual design
4. Simplified PRA for the system
5. Definition of analytical tools
6. Preconceptual design and analysis of safety features
7. Simplified preliminary environmental impact statement for the system
8. Preliminary safeguards and physical protection strategy
9. Consultation(s) with regulatory agency on safety approach and framework issues.

The data needed to evaluate the viability of these systems will be gained largely through modeling and simulation. In non-nuclear technology development programs modeling and simulation is part of the earliest, least mature stages of a development program. Those non-nuclear systems either have significant knowledge about the basic science related to their areas or the barriers (mostly cost) preventing them from building large physical testbeds to evaluate the systems are small. For Gen IV, the cost of building multiple physical systems just to demonstrate their viability is cost prohibitive and not necessary. Much of the data can be culled from models and simulations. For the purpose of the Gen IV evaluation scale, more understanding of this modeling work and its impact on maturity advancement was needed.

3.1.2 TRL Scale Used for this Analysis

For Gen IV, expanded levels of detail were added in the Concept Development and early Proof-of-Principle areas. These additional levels pertain to the development of tools needed to be able to analyze, evaluate, or perform fundamental applied tests in certain areas of the Gen IV systems. An example of such research would be the development of material testing standards. Several Gen IV systems will use new materials due to the high operating temperature of the reactor system. There are no standards for testing some of these materials. The development of testing standards is a necessary predecessor to actually being able to evaluate materials and their properties as they relate to the operating envelope and service associated with the Gen IV systems. The definitions of the TRLs are provided below.

3.1.2.1 ***TRL Definitions.*** For Gen IV, the system concepts have already been identified. These are the six main reactor system types. The identification of those concepts defines the first level of the TRL, Concept Identification. After that, TRL levels 2-5 were expanded to provide a finer division for monitoring progress.

As stated, most TRL assessment tools assume that tool preparation and development activities have already occurred, i.e. there are ways of measuring the properties of interest, there are standards for testing the material under study, there are systems for evaluating the chance of element success, etc. For Gen IV this is not an assumption that can be made, or if it were made it could lead to a lack of recognition of progress in the developing or preparing of the tools needed to actually perform some of the R&D. It was also determined through some of the initial reading of the report summaries that many of the reports document the preparation and up-front work needed prior to even developing a tool for application to a given system, sub-system, or component. Other reports actually document the application and discuss the results. This provided a second level of expansion:

1. Tool preparation
2. Tool development
3. Tool application planning
4. Tool application execution

The most easily determined structure for monitoring the maturity of the preparation or the execution of a tool or method was to assess the basis of application of the tool in question. That means that the documentation was examined to see what part of the Gen IV system the tool was being applied to. If the tool being developed could be applied to the entire Gen IV system but was only being applied to a sub-system or component of the system, then it was determined to be of lower maturity and lower readiness level. The primary assumption needed for this part of the assessment is that tools and methods progress in maturity as they are applied to more complex versions of the system, and complexity is related to the scope within the study (larger scope with more elements - sub-systems vs. components, systems vs. sub-systems - equates to more complexity of the tool). As the given tool can be applied to more complex definitions of the integrated systems, it becomes more robust and more mature.

The scale of tool application provided a second mode of expansion for the TRL levels:

A. Building-block or component
B. Assembly or sub-system
C. Integrated system

The development of tools and the execution of those tools on the Gen IV building blocks, sub-systems, and systems do not occur as a step-by-step flow within the two top level breakdowns. The tool preparation as it pertains to a system building block is often immediately followed by the planning and execution of the tool with respect to the building block. Therefore, there is an alternating between tool development and tool execution as the system progresses through the maturity scale.

The above elements combine to form the following detailed structure for assignment of TRL:

Table 3. TRL assignment structure and comparison to AFCI scale (Table 1)

Generic TRL Scale			**Proposed Gen IV TRL Scale**	
TRL	**Category**	**Description**	**Top Level Description**	**TRL Label and Numerical Reference (see description in section 3.2)**
1	Concept Development	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development.	Concept Identification	1
2		Practical applications are invented. Applications are speculative and there may be no proof or detail to support assumptions	Tool Development	Building block or component, tool planning; 2.1
				Building block or component, development; 2.2
			Tool Execution	Building block, test planning; 2.3
				Building block, execution; 2.4
3		Active research and development is initiated. This includes analytical and laboratory studies to physically validate analytical predictions or separate elements of technology.	Tool Development	Sub-system, tool planning; 3.1
				Sub-system, development; 3.2
			Tool Execution	Sub-system, test planning; 3.3
				Sub-system, execution; 3.4

Generic TRL Scale			Proposed Gen IV TRL Scale	
4		Integration of basic technological components for testing in laboratory environment. Includes integration of "ad hoc" hardware in the laboratory.	Tool Development	System, tool planning; 4.1 System, development; 4.2
5	Proof-of-Principle	Integration of basic technological components with realistic supporting elements for testing in relevant environment.	Tool Execution	System, test planning; 5.1 System, execution; 5.2
6		Model or prototype system testing in relevant environment	Demonstration	NA[2]
7		Demonstration of prototype system in an operational environment at the engineering scale.		
8	Proof-of-Performance	End of system development. Technology proven to work in operational environment at the engineering to full scale.		System level physical mockup, integration and verification/validation of previous model and simulation results; 8
9		Full scale application of technology in its final form at mission conditions.		Demonstration; 9

3.2 Summary of R&D Results

Each Gen IV R&D report documents either a specific task designed to provide information for a specific technical need, or a summary of the work to-date in a given area that will eventually provide such information. A set of questions was developed that would provide both information to help with the assessment of the TRL for the system based on the reported information as well as to help the Project Manager assess the health of the overall R&D program and its progress towards Gen IV goals.

3.2.1.1 The Five Questions. A vast amount of technical and programmatic information is provided in the reports that were examined. A subset of that information is applicable to evaluating the TRL of the system. Therefore, the analysis focused on: (1) maintaining/documenting the least amount of information in the document need to provide context of where the research reported is in terms of

[2] These TRLs would most likely be skipped for Gen IV systems, as it is unlikely that physical models or demonstrations would occur at any scale below full. The costliness of integrated, full-system physical demonstration would probably demand it be built at nearly full scale or that the intended actual system would be used for testing.

technical life cycle maturity, and (2) honing the information for rating each document into a relatively small but sufficient amount of information that could be independently verified and validated.

To meet those requirements, a set of questions were developed and consistently applied to all documents in order to capture the necessary information. The set of questions that were developed are:

1. What is the problem that research is being undertaken to solve?

2. Why is that research relevant the particular Gen IV reactor system?

3. What has been accomplished to date,

4. Amount of effort in fractions of millions of dollars (plus if not too difficult to obtain - duration of task reported)

5. What is the next step?

From that derived information, an even smaller set of information was used to assign a TRL to each document. The first two questions and the last are context questions. Those questions set the position of the documented research in four different viewpoints.

1. Technical domain (science – engineering)

    a. Core Fuel & Materials
    b. Reactor systems
    c. Balance of Plant
    d. Fuel Cycle
    e. Risk and Safety
    f. Protection
    g. Analysis Tools

2. Time (activity) to tie it back to a previous activity in the R&D Roadmap – Program management

3. Physical granularity (from the finest to the coarse) – systems perspective

    a. Building Block (e.g. building block could be basic science, a model, a new material, a fuel, or some part of the fuel cycle),
    b. Subassembly,
    c. Unit Assembly,
    d. integrated prototype,
    e. or a full scale demonstration problem and

4. Why is this research being done – what is the driver?

The third question aids in setting the "stake" from those four perspectives. The fourth question is used to validate, if the information was available, either cost to date or time consumed that the stake set in four was consistent with previous estimates.

3.3 Assessment and Visualization of TRLs

3.3.1 Technology Readiness Level (TRL) Assignment Methodology

After gathering the information that corresponds to the questions from Section 3.2.1.1, the next step in the process is to assess the information in the context of assigning a TRL for the reported information. Another way to look at the TRL is to consider it from a technical maturity standpoint. The farther along the effort is in solving problems and producing information related to making a working VHTR system, the more mature the system is and, hence, the higher TRL a system would gain from the documented efforts. As stated below, the main difficulty in assigning an accurate TRL associated with an R&D effort comes from aligning the work to the physical system architecture that it is studying, understanding the implications of scale of the R&D effort, and understanding the actual steps in the specific R&D process that will lead to the answer that resolves the technical uncertainty being studied.

3.3.2 Gen IV Taxonomy

A taxonomy or listing of the functions that the system performs is needed for this transition. Information regarding a breakdown of Gen IV functions is defined in "A Technology Roadmap for Generation IV Nuclear Energy Systems" [NERAC and Gen IV, 2002] and "Generation IV Roadmap R&D Scope Report for Gas-Cooled Reactor Systems" [NERAC and Gen IV International Forum, 2002]. This information can be used to develop the following Gen IV generic taxonomy.

Table 4. Generic Gen IV taxonomy

1.	**Gen IV Reactor Type**
1.1	**Core Fuel and Materials**
1.1.1	Reactor Vessel Materials
1.1.2	Core Internal Materials
1.1.3	Other Structural Materials
1.1.4	Time Process for Evaluation of Fuels and Materials
1.1.5	Fuel Properties
1.1.6	Fabrication
1.1.7	Remote Maintenance
1.2	**Reactor Systems**
1.2.1	Maintenance
1.2.2	Screening and Testing
1.2.3	Inservice Inspection
1.2.4	Refueling
1.2.5	Materials and Components
1.2.6	Decay Heat
1.2.7	Core Heat Transfer
1.2.8	Enthalpy Transport

1.2.9	Reactor Neutronics and Control
1.2.A	Coolant Chemistry
1.3	**Balance of Plant**
1.3.1	Energy Product Conversion
1.4	**Fuel Cycle**
1.4.1	Fuel Source
1.4.2	Fuel Disposition
1.5	**Risk and Safety**
1.5.1	Safety and Reliability Evaluation, Peer Review
1.6	**Economics**
1.7	**Protection**
1.8	**Design and Evaluation**
1.8.1	Preconceptual
1.8.2	Viability
1.8.3	Conceptual Design
1.8.4	Other
1.8.5	Analysis Tools

There are 8 primary system areas addressed in the taxonomy with some additional breakout to show important sub-system details. Additional breakdown does not currently add value from a maturity development perspective but may be needed for specific reactor systems to highlight unique sub-systems. Furthermore, the building block (component) level of the system is not shown for simplicity.

The taxonomy shows the various areas of the Gen IV system. The documentation summary contains the area of the system that the R&D work is focused on. By combining those two pieces of information, the TRL related to the documentation can be assigned.

3.3.2.1 Checking Applicability of the Gen IV Taxonomy. As the documentation is being analyzed for a given Gen IV system, the taxonomy in Table 4 must be evaluated for sufficiency. For example, if a document covers an element of the system that is related to a sub-part of the balance of plant, then this element should be added to the taxonomy above to show its place in the taxonomy. It is not expected that additional system level elements would be needed as this taxonomy comes from Gen IV system documentation. Future program changes, though, could identify additional areas of study and modification of the above taxonomy may be required.

3.3.3 R&D Activity

As stated in the definition of the TRLs, there are two main aspects of the R&D work that determine the resulting TRL: 1). the aspect of the Gen IV system being focused on and 2). the activity being performed on that aspect of the system. For example, a particular R&D task may involve developing material property parameters for novel materials. The purpose of the development of the material property parameters is to either aid in actual materials testing or aid in design of a given sub-system. Either way, the material properties are building blocks for the sub-system level materials, and the activity being performed is one of tool development. Now, if the documentation is actually addressing the development of the material property parameters rather than the development of *the plan* to develop the material property parameters, then this R&D would fit in the category of tool development of a building block. Using Table 3, this would equate to a TRL of 2.2. Understanding both the subject of the R&D (tie to taxonomy) and the activity being performed on that subject (tie to TRL) is required to accurately assess the TRL.

3.3.4 Visualization Method

A graphical visualization method was chosen to display the TRL assignment results. As it was anticipated that there would be more than one document focused on a given aspect of the Gen IV system, a way to see not only the average TRL score for a given aspect of the system but also the range of TRLs associated with the work performed on that part of the system was needed. Figure 1 is an example of the TRL visualization method.

The bars show the nominal TRL rating for the given element, while the black lines denote the ranges of rating that could have been assigned based on the documentation that was examined. These black lines should not be considered “error bars” in terms of the standard statistical definition. Instead, they show the range of TRLs ratings that could be interpreted from reading individual reports associated with the taxonomical element. The rating provided by the blue bars represents that most of results for that taxonomy element hit that TRL score.

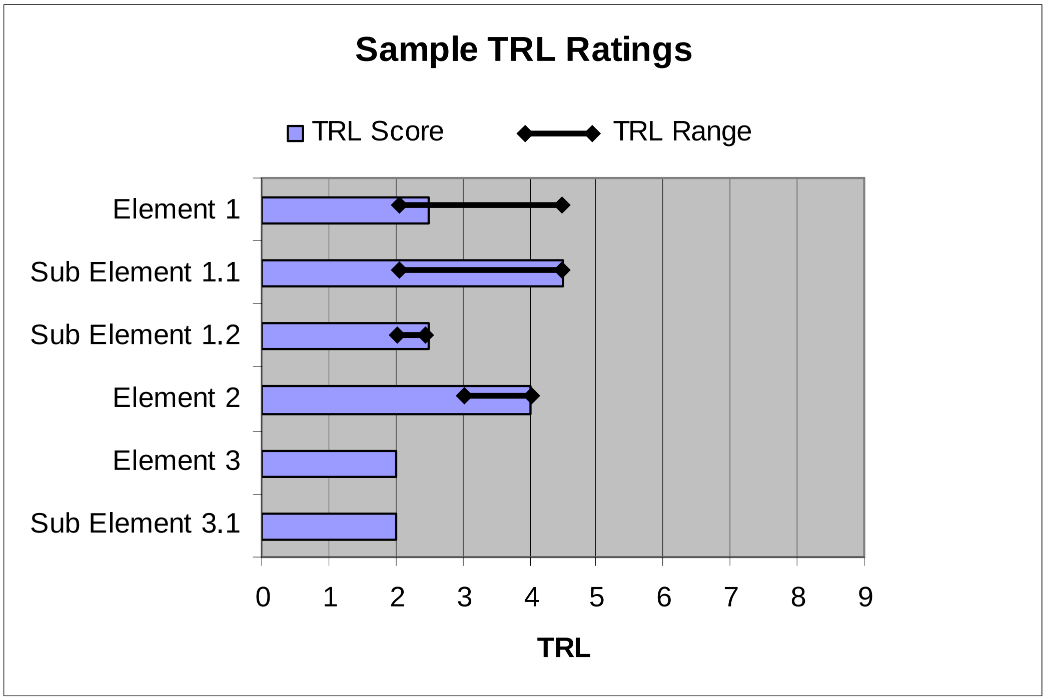

Figure 1. Sample TRL visualization.

3.4 Overall TRL Determination Process Flow

The overall process for TRL determination is shown in Figure 2.

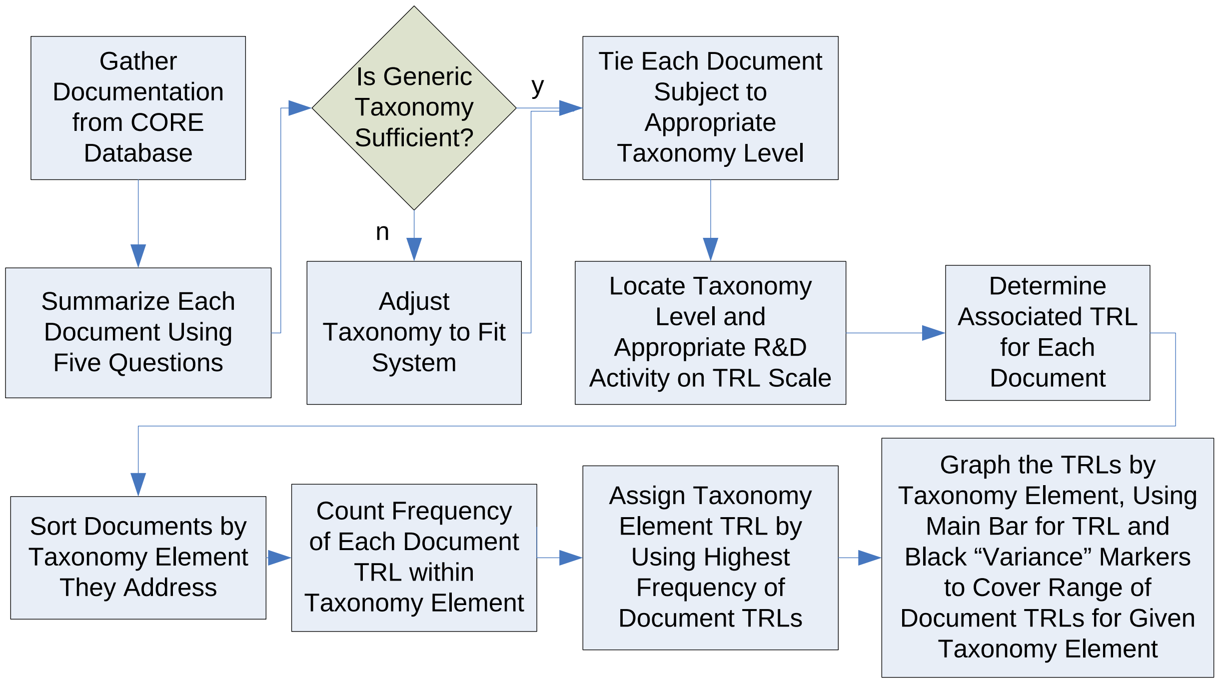

Figure 2. Process flow for TRL determination.

4. Specific Prototype Application

As stated, the general approach was applied to a specific reactor system within the Gen IV domain. Also, the reports that were evaluated were limited so that the application could be accomplished in a timely fashion and represent a specific snapshot in time.

4.1 Limitations

4.1.1 Limitation – Reactor System Scope

The prototype methodology was applied only to the Very High Temperature Reactor (VHTR) system within Gen IV. The rationale for this limitation includes:

- The majority of the documented R&D for the period of interest were performed on VHTR issues,
- The System Integration Manager (SIM) and many of his staff were located in proximity to the performers of the analysis,
- The VHTR is the first Gen IV system that has been advanced through mission need approval and is entering conceptual design.

Initially, plans were to analyze only the gas-cooled variant of the VHTR, which is the reference design for the system. However, 20% of the documents available within the overall VHTR domain included R&D on the liquid salt cooled variant of the VHTR (LS-VHTR). It was determined in the flow of the work to include the documentation of LS-VHTR work in the prototype application process.

4.1.2 Limitation – Documents Developed in FY-05 Located on CORE

The preferred approach to evaluating the technical maturity of Gen IV reactor systems is to do so solely based upon evaluation of program documentation related to the R&D task results. This provides the ability to have specific basis of reference for the maturity evaluation and minimizes qualitative, subjective statusing. Input from SIMs and technical leads should only be used to supplement (in gap areas) or clarify. For this reason documentation of recent R&D efforts was examined to determine the technical maturity of the VHTR system. The source of documentation was purposely limited to the CORE database[3] once again to provide a specific domain basis.

CORE has been constructed for the main purpose of being a repository of information beneficial to the Gen IV program. Documentation of all R&D events that are related to milestones in the Gen IV program should be found in the CORE system.

For the purpose of providing a specific maturity status (versus a dynamic range), there must be a cutoff in time after which reports that were produced did not impact this analysis. It was determined that this cutoff would be at the end of FY-05. This is not very limiting, however, as very few milestone reports available on CORE were produced prior to FY-05.

[3] The database is found on the web at
http://comm.gen4forum.org/QuickPlace/core/Main.nsf/h_Toc/4df38292d748069d0525670800167212/?OpenDocument.

It is a limited access location requiring password authentication.

4.2 Summary of VHTR R&D Documentation

The VHTR documentation used for this analysis consisted of forty two VHTR documents produced in FY-05 found on the CORE database. The documents met the requirements for level 2 or 3 technical milestones and ranged from status reports to detailed technical reports. The full listing of the documents used can be found in Appendix A.

The information needed was first summarized from the actual content of the paper using the five questions (section 3.2.1.1). As an example, the box to the right contains the summary resulting from applying these questions to "Graphite Irradiation Creep Capsule AGC-1 Experimental Plan - MS 2-08" (found at http://comm.gen4forum.org/core) .

Graphite Irradiation Creep Capsule AGC-1 Experimental Plan - Ms 2-08 – 1). Codes nor data is available on the key data such as: a). Irradiation creep design data, and data on the effects of irradiation creep on key physical properties (strength, elastic modulus, CTE) b). effects of neutron irradiation on the properties of a wide range of NGNP relevant graphites, including, dimensional changes, strength, elastic modulus, thermal conductivity & CTE, &. c). Data on the single crystal irradiation behavior of graphites to be derived from Highly Oriented Pyrolytic Graphite. The data will be used to underpin the ASME design code being prepared for graphite core components. 2). These data are critical to the design of the NGNP and support ongoing work in the area of model development, e.g., irradiation effects model such as dimensional change and creep strain, structural modeling, and fracture modeling. 3). The report reviews the background and theory of irradiation induced creep in graphites, details the graphite grades to be irradiated in the experiment along with the rationale for inclusion & irradiation test conditions. Detailed AGC-1 layout plans are given for each of the specimen channels in the capsule, & the specimens are tabulated by grade, location & anticipated fluence. The process of pre- & post-irradiation examination, details of the tests to be performed, & the data to be acquired are presented, 4). TBD, and 5). Complete pre-irradiation examination of AGC-1 graphite specimens 3-31-06, Complete assembly of AGC-1 6-30-06, Complete AGC-1 out of core shake down testing 9-30-06, Reactor insertion 10-31-06, Complete irradiation 6-30-07, Complete hot cell disassembly 9-30-07, Ship graphite specimens to ORNL for PIE 10-31-07, Complete graphite PIE 6-30-08, Issue draft AGC-1 PIE report 9-30-08.

From that summary, a few sentences were developed that included the key words necessary to make the ties to the VHTR taxonomy (subject matter) and the TRL scale (R&D activity). The box below shows the key words used to assign the TRL level 2.

Having described the process used to evaluate the information supplied in the reports and the establishment of the resultant TRL range, the next section will show the results of applying the process and analysis.

An experimental plan. Outcome of experiment would support ASME design code for materials (code for building block - tool development, building block, preparation) and actual design data (design data for building block - tool execution, building block, evaluation). Since developing a plan leading to that information, would be considered building block preparation at the tool development level.

4.3 VHTR-Specific Taxonomy

Upon analyzing the generic Gen IV taxonomy provided in Table 4 no modification is needed to cover the unique aspects of the VHTR system. This validates the robustness of the generic taxonomy. Specifically, the Balance of Plant sub-systems do include the IHX and Turbine sub-systems, but their TRL can be rolled up into the Energy Product Conversion element. Also, the VHTR is currently defined to have a once-through fuel cycle, so the fuel cycle system and associated sub-systems of the taxonomy is not as pertinent. For completeness, it remains in this documentation.

Some of the elements of the taxonomy relate directly to physical aspects of the system. Other elements are actually themselves domains in which technical maturity will increase as R&D is conducted. For example, the intermediate heat exchanger is a physical part of the reactor system (for VHTR). It would mature from a technical perspective as research was performed to reduce uncertainties related to operation or performance of the heat exchanger. On the contrary, economics is not a physical aspect of the VHTR system, but it is an area of analysis that needs to mature as well. Methodology for analyzing the economics of the VHTR is an area of study managed by the crosscutting Economics Methodology Working Group, and it will mature as well as research is performed, both from a technical and from an economic evaluation perspective. The technical maturity of the physical elements is a more straightforward and better understood attribute to analyze, but the maturity of the economic analysis is also possible to measure and has been accounted for in the general methodology outlined above.

5. Results of Application to VHTR

A table that shows the complete evaluation results for the reports and their related taxonomy elements is provided in Appendix B. That table shows that the relationship of the reports to the taxonomy can be described as “many to many” in database terms. Each report may provide information that related to the TRL for many taxonomy elements, and each taxonomy element may have many reports providing information relating to TRL. The information regarding the taxonomy elements, number of related reports and overall TRL is provided in Figure 3.

The total of all the number exceeds forty-two due to the “many to many” relationship described above. To summarize Figure 3, the area that appears to have the most research is “Analysis Tools” and the areas that had no documents in are:

1. Economics, and
2. Protection.

The other information that can be obtained from the chart is that no area investigated is above level – Subassembly Evaluation, or level 3.4. In fact of the 16 areas reported, only two “Risk and Safety” and “Analysis Tools” had the largest range with the highest maturity level 3.4. The higher maturity of these areas should come as no surprise since both areas are essential to achieving licensing and demonstrating VHTR viability. That is one of the objectives of GEN IV - prove the reliability to regulators, the commercial industry and to the government. Of the remaining areas, five have only matured to the first level of maturity – 2.1, four to 2.2, and five to 3.3. The TRLs for the VHTR system, based on the information evaluated suggests that the system is in the earliest phases of research. (Later sections of this report evaluate the potential that additional information would suggest a much higher overall rating.)

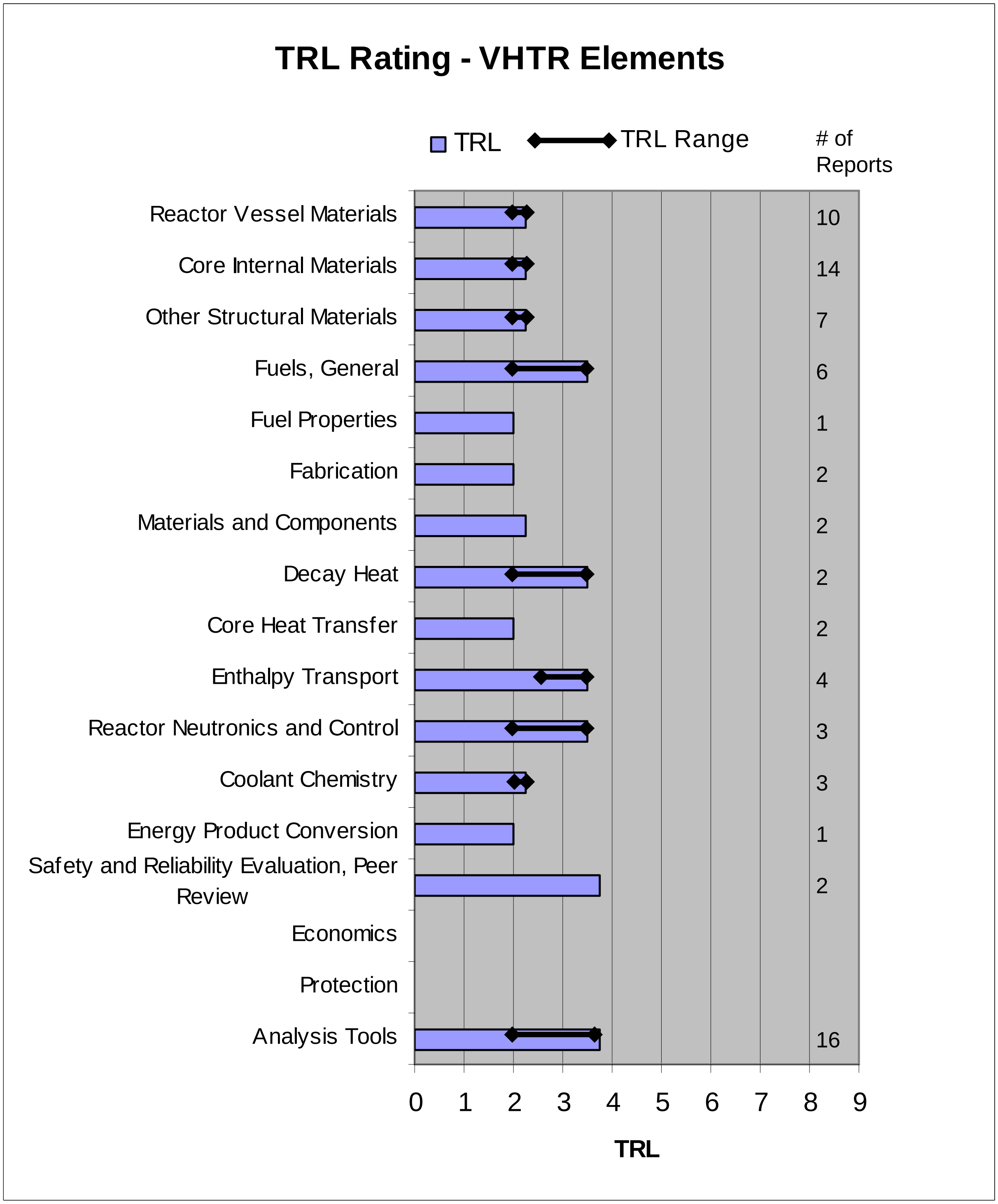

Figure 3. TRLs for VHTR based on this analysis

6. Post-Analysis Evaluation

Since this effort is a prototype application of the maturity evaluation method, part of the process was to analyze the results by reviewing them with the System Integration Manager (SIM) for the VHTR program. Findings of this review are presented below. This section also includes comparisons of the current state of technical maturity versus those that would have been forecast from original work planning documentation as well as evaluation of expected maturity increase based on upcoming, planned work.

6.1 Calibration with SIM

A meeting was scheduled with the System Integration Manager (SIM) for the VHTR system. The purpose of the meeting was to provide a sense of the methodology used towards arriving at the above results and to present initial indications of those results.

The primary discussion during the meeting concerned the non-physical nature of the testing that would occur, and how to recognize the maturity of the overall system while still accounting for isolated elements in the taxonomy that are still at a basic science or research level. The SIM explained that most of the R&D associated with VHTR, especially at the sub-assembly and system levels, will occur in virtual environments of models and simulations. Without this physical connection in the tests performed, analysis of the maturity of the VHTR components and sub-systems becomes more difficult. This is one of the main drivers behind the development of greater granularity in the basic research and tool-building phases of the maturity scale. Once the models and simulations are built, and their complexity and “scale” increase, so does the maturity of this reactor system.

The SIM explained that VHTR is a leading reactor system because of the vast knowledge base and maturity of several elements of the system. Many reactors have been constructed and built that basically contain the main aspects of the VHTR system; they were just operated in a lower temperature regime and were built to meet different performance requirements (generally not as advanced as VHTR). Those changes in performance requirements and operating envelopes do cause fundamental changes in certain aspects of the system (core and structural materials, fuel makeup, etc.) that send the maturity of those sub-systems and components back to a very early stage. This does not change the fact that VHTR is one of the most mature systems in the Gen IV arsenal. Therefore, the SIM placed high value on being able to recognize the advanced relative maturity of VHTR without losing the understanding of the elements that require the most effort.

Overall, the meeting with the SIM confirmed aspects of the methodology development and provided other areas of emphasis. The issue associated with much of the testing domain being virtual was already solved, to an extent, by the increased granularity and credit given for development of those models (tools) that would become so vital to the R&D coming in the next phase of the program. The understanding of the importance of not just representing the maturity of what was documented in terms of the R&D results but also of the other parts of the system that are not being focused on in this stage of the program (due to their advanced relative maturity) was re-emphasized and one that was more difficult to deal with from a scope perspective. Based on these discussions, the maturity for the turbine / generator sub-system and the energy product conversion sub-systems would be high enough that it is possible to proceed with no additional research and development. Furthermore, fundamental understanding exists about how the VHTR operates (especially the reference system, Prismatic block fuel type), just not at the high temperatures or with the requirements set for the Gen IV version. That understanding can translate into knowledge and, by corollary, higher TRL in some reactor performance areas. Still, these understandings must at least be documented or referenced to be usable in VHTR design.

6.2 Progression of Technical Maturity over Time – Comparison to Expectations

In Section 3.3.1, the systems architecture taxonomy was introduced. This taxonomy was not fully addressed in the documentation studied. Furthermore, the analysis was focused on physical aspects of the VHTR system and the analysis tools. It is important to see the gaps this analysis leaves in reference to the overall taxonomy, and this is presented in Table 5. The gaps shown in Table 5 must then be analyzed in order to understand the reason for them.

Table 5. Graphical comparison of the two taxonomies.

Covered?	Taxonomy	
	1.1 Core Fuel and Materials	
yes	1.1.1	Reactor Vessel Materials
yes	1.1.2	Core Internal Materials
yes	1.1.3	Other Structural Materials
no -> GAP	1.1.4	Time Process for Evaluation of Fuels and Materials
yes	1.1.5	Fuel Properties
yes	1.1.6	Fabrication
no -> GAP	1.1.7	Remote Maintenance
	1.2	Reactor Systems
no -> GAP	1.2.1	Maintenance
no -> GAP	1.2.2	Screening and Testing
no -> GAP	1.2.3	Inservice Inspection
no -> GAP	1.2.4	Refueling
yes	1.2.5	Materials and Components
yes	1.2.6	Decay Heat
yes	1.2.7	Core Heat Transfer
yes	1.2.8	Enthalpy Transport
yes	1.2.9	Reactor Neutronics and Control
yes	1.2.A	Coolant Chemistry
	1.3 Balance of Plant	
yes	1.3.1	Energy Product Conversion
yes	1.4 Fuel Cycle	
	1.5 Risk and Safety	
yes	1.5.1	Safety and Reliability Evaluation, Peer Review
yes	1.6 Economics	
yes	1.7 Protection	

Covered?	Taxonomy	
	1.8 Design and Evaluation	
no -> GAP	1.8.1	Preconceptual
no -> GAP	1.8.2	Viability
no -> GAP	1.8.3	Conceptual Design
no -> GAP	1.8.4	Other
yes	1.8.5	Analysis Tools

It is assumed that the differences are indicative of one of four possible alternative rationales. These are:

1. The technology is so mature little R&D was needed in FY-2005. This alternative can be validated by reading documentation associated with the early planning or through discussion with the SIM and PIs from the project. The fuel is one example of this. This will be noted in upcoming tables as rationale A1.
2. R&D is needed, but no funding became available. This should be validated by looking at projected funding for each line of research vs. actual funding. This will be noted in upcoming tables as rationale A2.
3. The element was under-emphasized for other reasons and the importance of documenting the issue was not communicated. For example, either a cross-cutting area, commercial industry or another country is doing the research or has done the research and is suppose to be sharing their results with the VHTR SIM. This will be noted in upcoming tables as rationale A3.
4. R&D is needed once the first of the kind is assembled, (i.e. in-service maintenance is going to require a large core is built, refueling can start operations, etc.) and can not be done until after operations begins. This will be noted in upcoming tables as rationale A4.

To determine which of these alternative explanations are true, a review of two R&D documents was completed [NERAC and Gen IV International Forum, 2002, NERAC and Gen IV International Forum, 2002]. The documented assumptions that could be found about the technology are shown in Table 6. One of two assumptions is expected, either that the maturity is developed far enough that no R&D is needed at this time or other GEN IV programs are doing the work. For example, much of the R&D for the fuel is not being done by this program but is assumed being done by the Pebble Bed Reactor project or the Prismatic Modular Reactor project [NERAC and Gen IV International Forum, 2002]. The review found limited references for the gap areas, but these references were usually sufficient to classify each area per the four rationales (See 4th column of Table 6).

6.3 Upcoming Milestones and the Expected Impact on Maturity

Future efforts should advance the VHTR technical maturity to varying degrees. It is valuable to understand the expected change in maturity so as to track that expectation versus actual outcomes. In order to evaluate the expected change in maturity, upcoming milestones were reviewed and analyzed in the context of the TRL scale. The milestones were taken from the VHTR R&D schedule in the document entitled "*Generation IV Roadmap R&D Scope Report for Gas-Cooled Reactor Systems*" [NERAC and Gen IV International Forum, 2002] (see Figure 3). Table 6 reviews the previous program planning information and defines an expected completion percentage for the taxonomy areas that were not addressed in FY05.

The expected percent complete is based upon amount of time expected to be spent to date (identified by the double wide line on Figure 3) divided by total projected time. The fourth column of table 6 refers to the four alternate rationales listed in the previous section. The last column is important to the overall analysis, but many of the omitted taxonomy elements have not been addressed in the current planning horizon (through 2015) according to the referenced documentation. Also, for completeness, this is important information to gather and present for each taxonomy element, not just those that were not addressed.

Further analysis is needed before making conclusive statements as to needed funding in an area. Such analysis would include incorporating information found in FY-2006 R&D documents, review of Memorandums of Agreements and Memorandums of Understanding with other GEN IV partners and industry, and searching the VHTR repository of knowledge (assumes it exists outside the CORE database).

Table 6. Upcoming activities and impact on maturity

Omitted Taxonomy type	**Actual or Expected Start Date**	**Expected Percent complete**	**Alternative Rationales for Omission**	**Expected TRL upon Completion**
Reactor - Time Process for Evaluation of Fuels & Materials	Started 2002	*There was insufficient information found to answer the % complete.*		
Reactor - Maintenance	No projected time to start before 2015	Not Applicable (NA)	A4. Not feasible to start before then due to evolution of the VHTR technology	NA (beyond documented planning horizon)
Reactor - Screening and Testing	No projected time to start before 2015	NA	A4. Not feasible to start before then due to evolution of the VHTR technology	NA (beyond documented planning horizon)
Reactor - In-service Inspection	No projected time to start before 2015	NA	A4. Not feasible to start before then due to evolution of the VHTR technology	NA (beyond documented planning horizon)
Reactor - Refueling	Started 2002	60% complete	A2: Need to look at projected funding for each line of research vs. actual funding	To be determined. (TBD)
Turbine/Generator	Started 2002	60% - VH1 Milestone in 2008	A3: Expected to be done by aerospace industry as part of gas turbine development.	TBD

Omitted Taxonomy type	Actual or Expected Start Date	Expected Percent complete	Alternative Rationales for Omission	Expected TRL upon Completion
Energy Product Conversion	NA	VH2 Milestone in 2011	A3. See Separate Crosscutting Area	TBD
Fuel Cycle	Started 2002	25% complete	A3. See Separate crosscutting documentation	TBD
Economics	Does not start until 2015	NA	A3. See Separate crosscutting documentation	TBD
Protection	NA	NA	A3. See Separate crosscutting documentation	TBD
Design and Evaluation	Started 2002	25-30% complete	Note this is an overarching area	
Preconceptual	Started 2002	33 % complete		
Viability	VH3 is not until 2011	*There was insufficient information found to answer the percent complete.*		
Conceptual Design	Does not start until 2010	*There was insufficient information found to answer the percent complete.*		

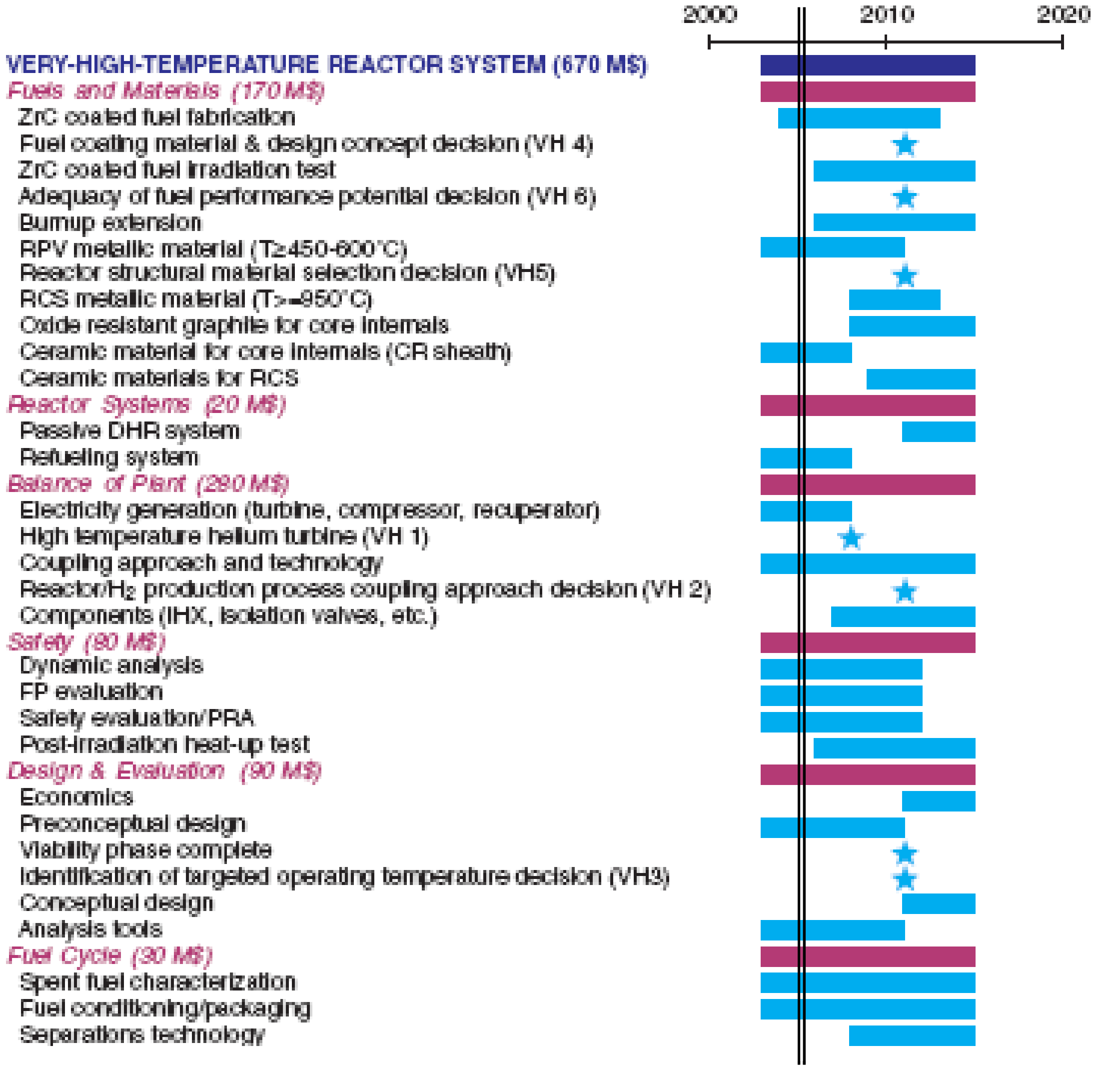

Figure 4. Projected VHTR R&D schedule

7. Issues, Method Gaps, and Recommendations

The development of the evaluation methodology for technical maturity of one Gen IV reactor system has led to findings related to both the evaluation process itself as well as the structure of project management, information management, and report documentation techniques. In order to structure a coherent set of recommendations, these issues must be placed in the order that has the most beneficial impact on the Gen IV program, namely project management, report documentation, information management, and technical maturity evaluation method, in that order.

7.1 Project Management as Related to Maturity Development

Currently, to an investigator outside the Gen IV program, it would seem that the logical drivers for R&D come from, first, the Gen IV technology roadmap and then, through allocation from the roadmap, to the individual annual technology plans. Perusal of those workplans and development of relationships to the original roadmap suggest many areas of development are behind schedule.

Difficulties in establishing these relationships between the technology roadmap and the annual workplans are caused by the lack of specificity of the technology needs and their status. The roadmap did lay out general areas of attack (materials, neutronics, fuels, etc.), but did not identify specific technology gaps nor their predecessor-successor relationships in terms of their resolution.

- Recommendation #1 – A detailed, updated technology gaps analysis should be performed to analyze the full suite of technical needs remaining to establish the viability of the reactor systems. That analysis should then be turned into a detailed plan for resolution of those uncertainties. This could be documented in a revision to the roadmap or in an execution plan.

Such a document would allow for a clear understanding of what is left to do, how long it will take, what the predecessor-successor relationship of the resolving activities are, and how the budgetary constraints impact project timing. Likewise, the document would be the springboard for future R&D task planning and a reference point for each R&D document to refer in terms of the relevance and context of its work. This would greatly aid technology maturity evaluation in the future.

7.2 Report Documentation

One purpose of the R&D efforts that are funded by the Gen IV program is to advance the applicable maturity in terms of technical maturity. Usually, that is accomplished through performing research to answer questions that are still open regarding the performance or viability of the system in question. It should be clearly stated in the documentation of that research, beginning in the executive summary and highlighted throughout the document, which question the R&D endeavors to answer and how that relates to the advancement of the studied system. Often this clarity was lacking from the milestone documents examined.

Also, there are times when R&D is not fully successful. There are objectives defined for each R&D workscope. Due to any number of foreseen or unforeseen circumstances an R&D effort might not meet all of its objectives. Not only should each document clearly explain the objectives of the effort, but the documentation should state whether or not the R&D was fully, partially, or not at all successful in terms of meeting the objectives.

- Recommendation #2 – All R&D reports should specifically indicate the Gen IV reactor system and the technical need being addressed, clearly stating the purpose of the R&D with respect to that need and system, and the degree to which the R&D was successful.

Planning should emphasize that viability related uncertainties should be resolved prior to performance specific or optimization related issues being worked. That way, if a viability-impacting risk arises based on an R&D outcome; money is not simultaneously being spent on optimizing another aspect of the system in question. Therefore, it is important for project management to understand an effort in the context of what type of uncertainty it is resolving.

- Recommendation #3 – Compare scopes of work to identify efforts that may be addressing performance issues beyond the required level of understanding for the viability phase. Viability phase elements should be resolved prior to performance advancement.

Understanding the cost of R&D needed to resolve certain problems can be indicators of emerging high-risk areas. History has shown that some issues that are perceived to be low or medium risk due to the perceived low probability of actually coming to fruition can become sticking points in the development of a process or system. Repeated overspending or allocation of additional resources in a given area is a bellwether of such sticking points. This is another reason to have an accurate accounting of the money spent on R&D activities.

- Recommendation #4 – Ensure the dollars spent on each specific R&D effort be separately reported or otherwise available, and the associated documentation clearly identify the scope of that work so that the budgetary linkage can be made in an accurate manner.

7.3 Information Management

It is clear that there is information related to the maturity advancement of the VHTR system that was not documented in CORE. In some cases, the information was documented, but either not as part of an official milestone document or part of a document that is not found on the CORE system. There are two probable reasons for this: the effort was funded by a source outside of Gen IV purview, or, more likely, the information is the result of effort that happened before Gen IV came into being. These two reasons are quite similar, but they indicate two different courses of action needed to resolve them.

Given that the CORE system exists and is the repository for the Gen IV program, it should be the data source for information regarding advancement of the systems in terms of technical maturity. Using tribal knowledge as a source of maintaining and distributing information is not effective and is subject to many breakdowns. In the case where reports documenting maturity-advancing results are not responsive to formal milestones, there should be other mechanisms to include the appropriate documents on the official repository system. Finally, there needs to be a specific effort to account for information that is related to the maturity of elements of the U. S. Gen IV systems that was generated prior to the existence of the Gen IV program. The source of the information should be documented and sought out. Once found, some method of linking to that information should be made so that at the appropriate time the information is accessible to the Gen IV program participants. This effort may identify that vital information thought to be readily accessible may not exist at all. A recovery plan would need to be included in future efforts for such an outcome.

- Recommendation #5 – Assure that all work performed under Gen IV funding that could relate to the technical advancement of any system or crosscutting area of study be included on the CORE system, whether it be a specific milestone or not. Furthermore, assure that all documentation related to accomplishment of milestones related to Gen IV is located on the CORE system.

- Recommendation #6 – Identify work and information developed under funding sources other than Gen IV, such as by international partnership or past technologies, that relate to the technical maturity of Gen IV systems or crosscutting areas. Link that work, with appropriate assignment of credit for authorship and funding, to the CORE database.

7.4 Improving the Technical Maturity Evaluation Methodology

Using a system that is purely related to the advancement of technical understanding as tied to the physical hierarchy of the Gen IV systems may not be the best approach. Some of the work related to materials, for example, a fundamental building block of several VHTR components and sub-systems is at a very basic stage. That does not mean that the whole VHTR system is at a basic science level of understanding. As the discussion with the SIM demonstrated, there are many areas in which the VHTR is quite advanced and may be ready to proceed to design. So, using a purely taxonomical approach to understanding technical maturity is not as beneficial as it would be if the whole system was progressing together (each component and sub-system was at the same level of development).

Beyond the aforementioned issue of important information not being found on the CORE system, there were other aspects of calibration that occurred upon meeting with the VHTR SIM. Several of the maturity measurement systems evaluated for this process, as mentioned in Section 3.3, significantly relied on the increase in scale and complexity of the test setups to determine technical maturity. The VHTR system, and most likely the other Gen IV systems, will not rely so heavily on physical, scaled-down setups but rather on modeling and simulation. Therefore, it is difficult for an outside, independent investigator to determine the technical maturity related to the VHTR without an intimate understanding of the maturity of modeling systems.

Furthermore, the discussion with the SIM showed that purely relying on the documentation can give a false sense of gaps and increased needs in the R&D program. Based on a certain periodicity of such a maturity analysis (a yearly update is recommended, timed to support annual work planning), it is recommended that the SIM or some PIs be engaged in the progress of the analysis so as to resolve any gap areas that are perceived to be significant. Such consultation should not occur prior to the start of analysis, as it may cause bias.

The approach defined here does help identify areas to look for technical gaps. Those technical gaps must be identified, and the work needed to resolve them quantified (in both budget and time). A detailed schedule can then be created documenting the predecessor-successor relationship of the work. This is the essence of recommendation #1.

If recommendation #1 is accepted and the detailed plan developed, evaluating the technical maturity becomes a straightforward exercise. Once a document is completed for a given task identified in the revised roadmap, a cursory review of the document would identify whether or not the task actually resolved the uncertainty in a satisfactory manner that would allow the program to advance to the successor task. If the task did not resolve the uncertainty, that does not mean that the task was a failure, but that more work must be done to achieve the technical advancement that is needed to move on.

By understanding what is needed to resolve the remaining uncertainties, the technical maturity can be communicated in the domain of remaining time or remaining budget needed. This is a very beneficial way to communicate from a project perspective rather than a science perspective.

7.4.1 Living Roadmap

For the essence of recommendation #1 and the subsequent evaluations to work effectively, the revised R&D plan must be a living document. As stated, there will be occasions when the result of tasks will not resolve the uncertainty and, indeed, may identify additional uncertainties. If the roadmap is updated only every two or three years, there will not be enough time to know how to recover from such a learning event.

8. Path Forward

8.1 Adjusted Methodology Application to VHTR

Specific technology needs and gaps for the VHTR system need to be identified and documented. A plan should be developed to resolve those gaps to the level of satisfaction of Gen IV leadership. Once that plan is in place, the existing document summaries plus the documents developed since the end of FY-05 can be reassessed to establish the progress towards resolving the technical uncertainties in the plan. This could be performed by the end of the fiscal year.

8.2 Application to Other Systems

Assuming to the above recommended approach modification; application to other system would take the same form. Attention would have to be paid to leveraging to the maximum extent the gaps and uncertainties that are common among reactor systems so that effort in defining the maturity of the given element related to that common gap is not duplicated. This is also necessary to demonstrate consistency in the analysis across the reactor systems. This could be performed in fiscal 2007.

9. References

B. Dixon and R. Soto, *Generation IV Nuclear Energy Systems Initiative Systems Analysis FY-2005 Year-End Report*, INL/EXT-06-11479, September 2005

U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, *A Technology Roadmap for Generation IV Nuclear Energy Systems*, GIF-002-00, December 2002

U.S. DOE Nuclear Energy Research Advisory Committee and the Generation IV International Forum, *Generation IV Roadmap R&D Scope Report for Gas-Cooled Reactor Systems*, 2002

R. Schultz, *GENERATION IV NUCLEAR ENERGY SYSTEMS PROGRAM PLAN*, Rev. 5, June 2003

Graphite Irradiation Creep Capsule AGC-1 Experimental Plan - MS 2-08

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Appendix A – Reports Analyzed for this Evaluation

1. Scaling Studies and Conceptual Experiment Designs for NGNP CFD Assessment - Milestone 2-01

2. Graphite Irradiation Creep Capsule AGC-1 Experimental Plan - Milestone 2-08

3. Initial Post Irradiation Examination Data Report for SGL NBG-10 Nuclear Grade Graphite-Milestone 2-13

4. AGC-1 Experimental Plan and Design Report - Milestone 2-14

5. Evaluation Of The Initial Critical Configuration Of The Htr-10 Pebble-Bed Reactor – Milestone 2-27

6. Development of an Experiment for Measuring Flow Phenomena Occurring in a Lower Plenum for VHTR CFD Assessment - Milestone 2-28

7. Status of Physics and Safety Analyses for the Liquid-Salt-Cooled Very High-Temperature Reactor (LS-VHTR) - Milestone 2-29

8. Structural Ceramic Composites for Nuclear Applications- Milestone 2-30

9. Chemical Considerations for the Selection of the Coolant for the Advanced High-Temperature Reactor (AHTR) - Milestone 2-55

10. Bounding estimate for the 'hot' channel temperature & preliminary calculation of mixing in the lower plenum for the NGNP point design using CFD - Milestone 3-08

11. Implementation of Molten Salt Properties into RELAP-3D/ATHENA - Milestone 3-104

12. Thermal-Hydraulic Analyses Performed For The LS-VHTR Description - Milestone 3-109

13. Completion of PEBBED-THERMIX Coupling - Milestone 3-11

14. Computation of Dancoff Factors for Fuel Elements Incorporating Randomly Packed TRISO Particles - Milestone 3-11

15. NGNP Graphite Testing and Qualification Specimen Selection Strategy - Milestone 3-115

16. POTENTIAL HELIUM TEST ENVIRONMENT FOR NEXT GENERATION NUCLEAR PLANT MATERIALS - Milestone 3-22

17. Development of a Controlled Material Specification for Alloy 617 for Nuclear Applications - Milestone 3-24

18. Scalability of the Natural Convection Shutdown Heat Removal Test Facility (NSTF) Data to VHTR/NGNP RCCS Designs - Milestone 3-36

19. Microstructure and Strength Characteristics of Alloy 617 Welds - Milestone 3-37

20. Development of a Fracture Toughness Testing Standard for Nuclear-Grade Graphite Materials - Milestone 3-38

21. Summary of SiC Tube Architecture and Fabrication - Milestone 3-42

22. Modeling of the Power Conversion Unit (PCU) - Milestone 3-44

23. Effects of Impure Helium Environments on Surface and Near-Surface Microstructures of Reactor Candidate Materials - Milestone 3-49

24. Development of Standardized Test Methods, Design Codes and Databases for SiC/SiC Components in Next Generation Nuclear Power Plant Systems - Milestone 3-50

25. Issue Preliminary Capsule Design and Experimental Plan for NGNP High Temperature Graphite Irradiations- – Milestone 3-53

26. Next Generation Nuclear Plant Carbon Composites Literature Review and Composite Acquisition - Milestone 3-55

27. Procurement and Checkout of Environmental Chamber" and "Status of Creep-Fatigue Testing of All 617 Welds - Milestone 3-58

28. Controlled Chemistry Helium High Temperature Materials Test Loop - 8/05 - Milestone 3-59

29. Initiation Of Scoping Tests To Provide Time dependent Input For HTDM Constitutive Equation Development - Milestone 3-60

30. Aging and Environmental Test Plan - Milestone 3-61

31. Uncertainty and Target Accuracy Studies for the Very High Temperature Reactor (VHTR) Physics Parameters - Milestone 3-64

32. Liquid Salt-cooled VHTR Neutronic Studies - Milestone 3-65

33. Natural Convection Shutdown Heat Removal Test Facility (NSTF) Evaluation for Generating Additional Reactor Cavity Cooling System (RCCS) Data, & CFD Analysis for the Applicability of the NSTF for the Simulation of the VHTR RCCS - Milestone 3-83

34. Evaluation of the DRAGON Code for VHTR Design Analysis - Milestone 3-84

35. Status of geometry effects on structural nuclear composite properties - Milestone 3-86

36. Creep of Structural Nuclear Composites - Milestone 3-87

37. FY05 Status Report On The Development And Application Of Coupled Codes For Pebble-Bed NGNP Analysis - Milestone 3-89

38. FY05 Status Report On The Development And Evaluation Of Spectrum Codes For Pebble-Bed NGNP Analysis - Milestones 3- 94

39. Validation Studies for Numerical Simulations of Flow Phenomena Expected in the Lower Plenum of a Prismatic VHTR Reference Design - Milestone 3-90

40. Very High Temperature Reactor Status Of Relap5-3d Model Development - Milestone 3-91

41. Preliminary Neutronic Studies for the Liquid-Salt-Cooled Very High Temperature Reactor (LS-VHTR) - Milestone 3-92

42. Investigation of the Molecular Dynamics Of Silicon Carbide And Graphite At High Temperatures Investigation Of The Molecular Dynamics Of Silicon Carbide And Graphite At High Temperatures – Milestone 3-93

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Appendix B – Evaluation Matrix

This matrix lists the 42 VHTR reports reviewed as part of the technical maturity evaluation (the columns) and the generic reactor system taxonomy (the rows). The matrix values indicate the TRL levels indicated by the reports with respect to the taxonomy elements.

VHTR	Scaling Studies and Conceptual Experiment Designs for NGNP CFD Assessment - Milestone 2.1-01	Graphite Irradiation Creep Capsule AGC-1 Experimental Plan - Ms 2.1-08	Initial Post Irradiation Examination Data Report for SGL NBG-10 Nuclear Grade Graphite '2.1-13	AGC-1 Experimental Plan and Design Report - Milestone 2.1-14	Evaluation Of The Initial Critical Configuration Of The Htr-10 Pebble-Bed Reactor	Development of an Experiment for Measuring Flow Phenomena Occurring in a Lower Plenum for VHTR CFD Assessment - Ms 2.1-2.18	Status of Physics and Safety Analyses for the Liquid-Salt-Cooled Very High-Temperature Reactor (LS-VHTR) - Milestone 2.1-2.19	Structural Ceramic Composites for Nuclear Applications- Ms 2.1-30	Chemical Considerations for the Selection of the Coolant for the Advanced High-Temperature Rea+H34ctor (AHTR) - Ms 2.1-55	Bounding estimate for the 'hot' channel temperature & preliminary calculation of mixing in the lower plenum for the NGNP point design using CFD - Ms 3-08	Implementation of Molten Salt Properties into RELAP-3D/ATHENA - Milestone 3-104	Thermal-Hydraulic Analyses Performed For The LS-VHTR Description - Ms 3-109	Completion of PE2.2D-THERMIX Coupling - Milestone 3-11	Computation of Dancoff Factors for Fuel Elements Incorporating Randomly Packed TRISO Particles - Ms 3-11
Core Materials & Fuels - Reactor Vessel								2.1		2.2				
Core Internals		2.1		2.1						2.2				
Other Structural										2.2				
Fuels			2.1		3.3					2.2				
Properties														
Fabrication														
Reactor Systems - Materials & Components														
Decay Heat Removal														
Core Heat Transfer														2.1
Enthalpy Transport											2.2	2.2	3.3	
Reactor Neutronics & Control														
Coolant Chemistry									2.1					
BOP - Intermediate Heat Exchanger														
Turbine/Generator														
Energy Product Conversion														
Fuel Cycle														
Risk & Safety - Safety & Reliability					3.3									
Economics														
Protection														
Analysis Tools	3.3					2.2	3.4			2.2	2.2		3.3	2.1

VHTR	NGNP Graphite Testing and Qualification Specimen Selection Strategy - Milestone 3-115	POTENTIAL HELIUM TEST ENVIRONMENT FOR NEXT GENERATION NUCLEAR PLANT MATERIALS - Milestone 3-2.12.1	Development of a Controlled Material Specification for Alloy 617 for Nuclear Applications - Milestone 3-2.14	Scalability of the Natural Convection Shutdown Heat Removal Test Facility (NSTF) Data to VHTR/NGNP RCCS Designs - Ms 3-36	Microstructure and Strength Characteristics of Alloy 617 Welds - Ms 3-37	Development of a Fracture Toughness Testing Standard for Nuclear-Grade Graphite Materials - Milestone: Ms 3-38	Summary of SiC Tube Architecture and Fabrication - Ms 3-42.1	Modeling of the Power Conversion Unit (PCU) - Ms 3-44	Effects of Impure Helium Environments on Surface and Near-Surface Microstructures of Reactor Candidate Materials - Milestone 3-49	Development of Standardized Test Methods, Design Codes and Databases for SiC/SiC Components in Next Generation Nuclear Power Plant Systems - Ms 3-50	Issue Preliminary Capsule Design and Experimental Plan for NGNP High Temperature Graphite Irradiations	Next Generation Nuclear Plant Carbon Composites Literature Review and Composite Acquisition - Ms 3-55	Procurement and Checkout of Environmental Chamber" and "Status of Creep-Fatigue Testing of All 617 Welds - Ms 3-58	Controlled Chemistry Helium High Temperature Materials Test Loop - 8/05 - Milestone 3-59
Core Materials & Fuels - Reactor Vessel		2.1	2.1			2.1	2.1		2.1					2.1
Core Internals	2.1	2.1				2.1				2.1	2.1	2.1		2.1
Other Structural		2.1				2.1			2.1					2.1
Fuels		2.1				2.1								
Properties	2.1													
Fabrication					2.1		2.1							
Reactor Systems - Materials & Components		2.1												2.1
Decay Heat Removal								3.3						
Core Heat Transfer														
Enthalpy Transport				3.3										
Reactor Neutronics & Control														
Coolant Chemistry		2.2												2.1
BOP - Intermediate Heat Exchanger													2.1	
Turbine/Generator														
Energy Product Conversion														
Fuel Cycle														
Risk & Safety - Safety & Reliability								3.3						
Economics														
Protection														
Analysis Tools				3.3										

VHTR	Initiation Of Scoping Tests To Provide Time dependent Input For HTDM Constitutive Equation Development - Ms 3-60	Aging and Environmental Test Plan - Milestone 3-61	Uncertainty and Target Accuracy Studies for the Very High Temperature Reactor (VHTR) Physics Parameters - Milestone 3-64	Liquid Salt-cooled VHTR Neutronic Studies - Ms 3-65	Natural Convection Shutdown Heat Removal Test Facility (NSTF) Evaluation for Generating Additional Reactor Cavity Cooling System (RCCS) Data, & CFD Analysis for the Applicability of the NSTF for the Simulation of the VHTR RCCS - Ms 3-83	Evaluation of the DRAGON Code for VHTR Design Analysis - Milestone 3-84	Status of geometry effects on structural nuclear composite properties - Milestone 3-86	Creep of Structural Nuclear Composites - Ms 3-87	FY05 Status Report On The Development And Application Of Coupled Codes For Pebble-Bed Ngnp Analysis & FY05 Status Report On The Development And Evaluation Of Spectrum Codes For Pebble-Bed NGNP Analysis - Milestones 3-89	FY05 Status Report On The Development And Application Of Coupled Codes For Pebble-Bed Ngnp Analysis & FY05 Status Report On The Development And Evaluation Of Spectrum Codes For Pebble-Bed NGNP Analysis - Milestones 3-94	Validation Studies for Numerical Simulations of Flow Phenomena Expected in the Lower Plenum of a Prismatic VHTR Reference Design -Ms 3-90	Very High Temperature Reactor Status Of Relap5-3d Model Development - Milestone 3-91	Preliminary Neutronic Studies for the Liquid-Salt-Cooled Very High Temperature Reactor (LS-VHTR)	INVESTIGATION OF THE MOLECULAR DYNAMICS OF SILICON CARBIDE AND GRAPHITE AT HIGH TEMPERATURES– Milestone 3-93
Core Materials & Fuels - Reactor Vessel	2.1	2.1												
Core Internals	2.1	2.1					2.1	2.1						
Other Structural	2.1	2.1												
Fuels						2.2								
Properties														
Fabrication														
Reactor Systems - Materials & Components														
Decay Heat Removal					2.1									
Core Heat Transfer				2.1										
Enthalpy Transport														
Reactor Neutronics & Control			3.3	2.1									2.1	
Coolant Chemistry														
BOP - Intermediate Heat Exchanger														
Turbine/Generator														
Energy Product Conversion														
Fuel Cycle														
Risk & Safety - Safety & Reliability														
Economics														
Protection														
Analysis Tools	2.1		2.1			2.2			3.3	2.2	2.2	2.1		2.1